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INSTRUMENTATION FOR RADIOLOGICAL EMERGENCY RESPONSES

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The purpose of this report is to provide an overview of the instrumentation and associated techniques that would be used to perform radiological monitoring at an accident/incident involving the release of radioactive materials. This article is not intended to serve as a "user's manual" for the various instruments. However, it is intended to include sufficient detail to provide an appreciation of the limitations of field measurement techniques and thus provide a basis for proper application and use of such techniques in case of an emergency. For completeness, some elementary characteristics of different kinds of radiation are also included.

Quantitative measurements of radioactive contamination in the field is extremely difficult. Particles having short ranges, such as alpha and low energy beta radiation, are significantly and incalculably affected by minute amounts of dust or precipitation. Therefore, detection - rather than measurement - is a more realistic goal for alpha-beta surveys. More penetrating radiations, such as gamma and higher energy x-rays, are less affected by such overburden;

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however, these require special attention to field calibration techniques in order to convert meter readings to contamination estimates.

Field survey of uranium is best accomplished through measurement of x-rays in the 60-80 keV range emitted by uranium isotopes and daughters. For plutonium, the best technique is to detect the accompanying contaminant am-241, which emits a strong 60 keV x-ray. Knowing the original assay and the age of the weapon, the ratio of plutonium to americium can be accurately calculated and thus the total plutonium contamination determined.

Many of the overwhelming factors which cannot be controlled in a field environment can be managed in a laboratory; thus, all of the response services have mobile laboratory facilities which can be brought to an accident/incident site. Typically, the capabilities that can be brought to bear include gamma spectroscopy, low background counting for very thin alpha- and beta- emitting samples and liquid scintillation counters for extremely low energy beta emitters such as tritium.

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I. INTRODUCTION

1. Scope

The purpose of this report is to provide an overview of the instrumentation and associated techniques that would be used to perform radiological monitoring at an accident/incident involving the release of radioactive material. This article is not intended to serve as a "user's manual" for the various instruments. However, it is intended to include sufficient detail to provide an appreciation of the limitations of field measurement techniques and thus provide a basis for proper application and use of such techniques in case of an emergency. For completeness, some elementary characteristics of different kinds of radiation are also included.

Throughout this report, the word "radiation" will refer only to such nuclear radiations as might be found at a nuclear accident/incident.

2. Detection versus Measurement

Nuclear radiation cannot be directly detected by the human senses. (Even in extremely high fields, it is the damage being done to body cells, rather than the radiation itself, that is sensed.) Thus, radiation detection is always a multi-step, highly indirect process. For example, in a scintillation detector, incident radiation excites a phosphorescent material which de-excites by emitting photons of light which are focussed onto the photo-cathode of a photo-multiplier tube which triggers an electron avalanche which produces an electrical pulse which activates a meter which is read by the human operator. Not surprisingly, the quantitative relationship between the amount of radiation actually being emitted and the reading on the meter is a complex and sensitive function of many factors. Since control of those factors can only be accomplished well within a laboratory, it is only in a laboratory setting that true *measurements* can be made.

On the other hand, *detection* is the qualitative determination that radioactivity is or is not present. Although the evaluation of minimum levels of detectability is a considerable quantitative challenge for instrumentation engineers, the task of determining whether or not a meter records anything is generally considered much easier than the quantitative interpretation of that reading.

The above discussion suggests that the same equipment can be used for either detection or measurement. In fact, detectors generally have meters from which numbers can be extracted. However, to the extent that the user is unable to control factors which influence the readings, those readings must be recognized only as indications of activity (*detection*) and not *measurements*.

In the discussions that follow, it is essential to be aware of the limitations imposed by field conditions and their implications on the meaning of readings taken. We will therefore be careful to indicate the extent to which various instruments may be used as measurement devices or can only be used as detectors.

II. TYPES of RADIATION

1. General

Four major forms of radiation are commonly found emanating from radioactive matter: alpha, beta, gamma and x-radiation. The marked differences in the characteristics of these radiations strongly influence their difficulty in detection and consequently the detection methods used.

2. Alpha

An alpha particle is the heaviest and most highly charged of the common nuclear radiations. As a result, alpha particles very quickly give up their energy to any medium through which they pass, rapidly coming to equilibrium with and disappearing in the medium. Since nearly all common alpha radioactive contaminants emit particles of approximately the same energy (5 MeV), some general statements can be made about the penetration length of alpha radiation. Generally speaking, a sheet of paper, a thin layer (a few hundredths of a millimeter!) of dust, any coating of water or less than four centimeters of air are sufficient to stop alpha radiation. As a result, alpha radiation is the most difficult to detect. Moreover, since even traces of such materials are sufficient to stop some of the alpha particles and thus change detector readings, quantitative measurement of alpha radiation is impossible outside of a laboratory environment where special care can be given to such factors as sample preparation, detector efficiency and background interference.

3. Beta

Beta particles are energetic electrons, emitted from the nuclei of many natural and man-made materials. Being much lighter than alpha particles, beta particles are much more penetrating: for example, a 500 keV beta particle has a range in air that is orders of magnitude longer than that of the alpha particle from Plutonium, even though the latter has ten times more energy. However, many beta-active elements emit particles with very low energies. For example, tritium emits an 18.6 keV beta particle. At this low an energy, beta particles are less penetrating than common alpha particles, requiring very special techniques for detection. (See Section 7.)

4. Gamma and X-radiation

Gamma rays are an energetic form of electromagnetic radiation. As such, they are the most penetrating of the four radiations and easiest to detect. Once emitted, gamma rays differ from x-rays only in their energies, with x-rays generally lying below a few 100 keV. As a result, x-rays are less penetrating and harder to detect. However, even a 60 keV x-ray has a typical range of a hundred meters in air, and might penetrate a centimeter of aluminum. In situations in which several kinds of radiations are present, these penetration properties make x-ray/gamma ray detection the technique of choice.

5. Radiations from the Common Contaminants

The following table lists some of the commonly considered radioactive contaminants and their primary associated radiations.

TABLE 1. Commonly Considered Radioactive Contaminants and Their Primary Associated Radioactive Emissions

	Alpha	Beta	Gamma	X-rays
Ac-227		x		x
Am-241	x			x
Cd-109			x	
C-14		x		
Co-57			x	
Co-60		x	x	
H-3		x		
I-125				x
I-129		x		x
I-131		x	x	x
K-40		x		x
Pa-231	x			x
Pm-147		x		
Po-210	x			x
Pu-239	x			x
Ra-224	x			x
Ra-226	x			x
Ra-228		x		x
Sr-90		x		
Th-228	x			x
Th-230	x			x
Th-232	x			x
U(nat.)	x	x		x
U-235	x			x
U-238	x	x		x
Y-90		x		

III. Alpha Detection

Because of the extremely low penetration of alpha particles, special techniques must be employed to allow the particles to enter the active region of a detector. In the most common field instruments (AN/PDR - 56 and - 60), an extremely thin piece of aluminized mylar film is used on the face of the detector probe to cover a thin layer of phosphorescent material. Energy attenuation of the incident alpha radiation by the mylar is estimated to be less than 10%. However, use of this film makes

the detector extremely fragile: contact with literally any hard object, such as a blade of hard grass, can puncture the film allowing ambient light to enter the detection region and overwhelm the photomultiplier and meter. (Even sudden temperature changes have been shown to introduce stresses that can destroy a film.) In addition, contact with a contaminated item could transfer contamination onto the detector. Thus, monitoring techniques must be used which keep the detector from contacting any surface. However, recall that the range of the alpha radiation is less than four centimeters in air. This requirement to be within a few centimeters of monitored locations without ever touching one makes use of such detectors impractical except for special, controlled situations (e.g., monitoring of individuals at a hotline or air sampler filters).

As discussed above, the sensitivity (minimum detectability) of an alpha detector is not dictated by the ability of the active region of the detector to respond to the passage of an alpha particle; counting efficiency for alpha detectors is 25-60% of the alpha particles from a distributed source that reach the detector probe. Fortunately, alpha detectors in good repair normally have a fairly low background: there are few counts from cosmic and other spurious radiation sources and the elimination of most electronic noise is easy with current state-of-the-art instruments. As a result, count rates in the order of a hundred counts per minute or less are easily detectable on instruments such as the AN/PDR-60. However, the detectability is dominated by the ability of the alpha particles to get into the active region of the detector, which depends upon such factors as overburden (amount of dust and/or moisture lying between the alpha emitters and the detector), proximity of the detector to the emitters and thickness of the shield that covers the active region.

In simple demonstrations conducted at the BRL, a sealed alpha source (Am-241) was monitored with a well maintained AN/PDR-60 alpha probe and meter. Dust and water were sprinkled onto the source and changes noted. It was found that a drop of water, a heavy piece of lint or a single thickness of tissue paper totally eliminated all readings. A light spray of water, comparable to a light dew, reduced readings by 40-50%. A layer of dust that was just visible on the shiny source had minimal effect on the count rate; however, a dust level that was only thick enough to show finger tracks reduced readings by 25%. These simple demonstrations reinforced the knowledge that detection of alpha particles in any but the most ideal situations is most problematical. The leaching or settling of contaminants into a grassy area or the dust stirred up by vehicular traffic on paved areas will significantly decrease or eliminate alpha detection.

IV. Beta/Gamma Detection

Gamma rays and high energy (>1 MeV) beta particles are highly penetrating radiations. As a result, the major problems listed for alpha detection do not apply. Furthermore, at the energies of concern in nuclear weapon accidents/incidents, detection efficiency for most detectors is relatively high. Thus, beta/gamma detection is relatively easy.

Unfortunately, high energy beta and gamma radiation are not produced in the most likely radioactive contaminants (e.g. Plutonium, Uranium or Tritium). Rather, the major potential source of beta/gamma emitters is from fission product radioelements which could be produced in the extremely unlikely event of a partial nuclear yield. Beta/gamma detection, therefore, has no quantitative use in determining the extent of plutonium or uranium contamination, but is used as a safety precaution to determine any areas containing hazardous fission products.

Common gamma detectors are scintillation detectors (using scintillation media different from that described above for alpha detection) or gas ionization type detectors (ion chambers, proportional counters or Geiger counters.) In either case, the high penetrability of the radiation allows the detector to have reasonably heavy aluminum, beryllium or plastic windows and to be carried at a comfortable height. Dimensions of the active region of the detector (for example, the thickness of a scintillation crystal) can be made larger to increase sensitivity. Because the detection efficiencies are reasonably insensitive to energies in the energy regions of interest, the detectors can be calibrated in terms of dosage (rads or rem or roentgen), rather than in terms of activity: this practice reflects the common use for beta/gamma detectors.

Typical of a beta/gamma detector is the Ludlum Model 3 with a Ludlum 44-9 "pancake" (Geiger-Mueller chamber) probe. Minimum detectability for such a detector is a radiation field that produces readings 2-3 times greater than the background (no-contaminant, natural radiation plus electronic noise) reading. Customarily, this corresponds to a few hundredths of millirem per hour.

V. X-ray detection

For low energy (17-100 keV) x-rays, the scintillation detector is again the instrument of choice. Window thickness is again a factor, though not as significant as in the case of alpha detection. For example, the half-thickness for absorption of 17 keV x-rays in aluminum is 0.4 mm and in air is about four meters. These increase rapidly with energy. For 60 keV x-rays, the distances become 2.5 cm and 190 m respectively. Thus, for x-rays above 15 keV, an x-ray detector can be held at a comfortable

height above the contaminated surface.

The size of an electronic pulse produced by an x-ray in a scintillation-type detector is proportional to the energy of the x-ray. This has a most important application, commonly called pulse-height discrimination. Because of the relatively low (10s of keV) energy of the x-rays of interest, it is necessary that an x-ray detector and its electronics be quite sensitive. Unfortunately, such a detector is also sensitive to the myriad of radiations from natural sources and to common low-level electronic noise. The result is a deluge of signals that overwhelm the pulses from sought-after x-rays. In order to remove the unwanted signals, circuitry is installed in the meter to ignore all pulses whose size lies below a user-selectable lower level (threshold). In cases of high (natural) background, it is also useful to discard all pulses whose size is greater than a user-selectable upper level. The accepted pulses, therefore, are only those from the desired x-rays and that small amount of background that happens to fall in the same pulse-size region. The use of both upper and lower discriminator levels is commonly referred to as using a "window".

Unfortunately, pulse-height discrimination is not as "clean" as described above. In fact, the signals from the detection of identical x-rays will not be identical in size; rather, a large number of such detections will produce a distribution of pulse sizes which cluster about a mean pulse size. If one sets the lower-level discriminator slightly below and the upper level slightly above the mean pulse size, a large fraction of the desired pulses will be eliminated, resulting in a significant decrease in detector response. However, setting the discriminator levels far from the mean will admit too much background, thereby masking the true signals. (See Figure 1.) Thus, the setting of discriminator levels requires a qualitative judgement which can significantly affect the readings from a given contamination. Furthermore, since the width of the pulse size distribution depends in a most complicated way upon the condition and age of the detector, it is impossible to specify one setting for all similar instruments. Rather, techniques have been developed to establish the sensitivity of a given detector, with its electronics, in a field environment. This technique is described in the following section.

In spite of the above complications, the scintillation detector remains the instrument of choice for detection of x-ray emitting radioactive contamination. One such detector is the Field Instrument for Detection of Low Energy Radiation (FIDLER). (See figure 2.) A FIDLER (4 in. x 1 mm. NaI(Tl)) probe, in good condition, mated to a Ludlum 2220 electronics package, can detect 60 keV activity as low as 0.2 microcuries per meter. In a typical weapon-grade mix for a medium-aged weapon, this would correspond to about 1 microcurie of plutonium per square meter. Furthermore, since the x-rays are much less affected by

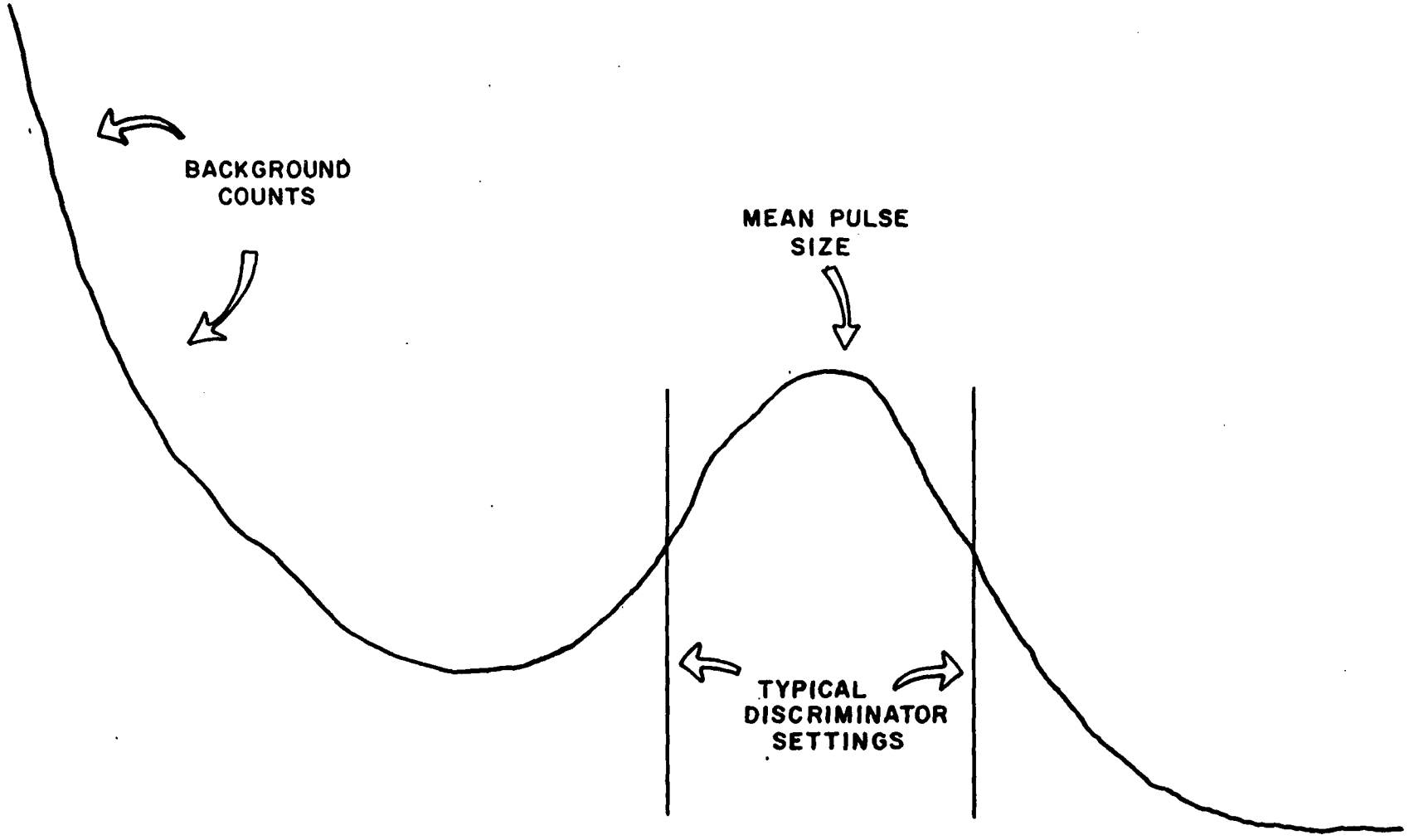


Figure 1. Spectral plot, showing normal spread of pulses from a mono-energetic source mixed with a typical background spectrum and indicating typical discriminator settings

overburden than are alpha particles, the radiation monitor has much better control of the factors which influence his meter readings. As a result, one can make quantitative measurements of the amount of radiation, and infer the actual amount of contamination, with far greater confidence than with any other field technique.

VI. Detection of Uranium and Plutonium

Although uranium and plutonium are alpha emitters, they - and their daughters - also emit x-radiation. Therefore, as discussed above, the instrument of choice for detection of these elements is a scintillation detector.

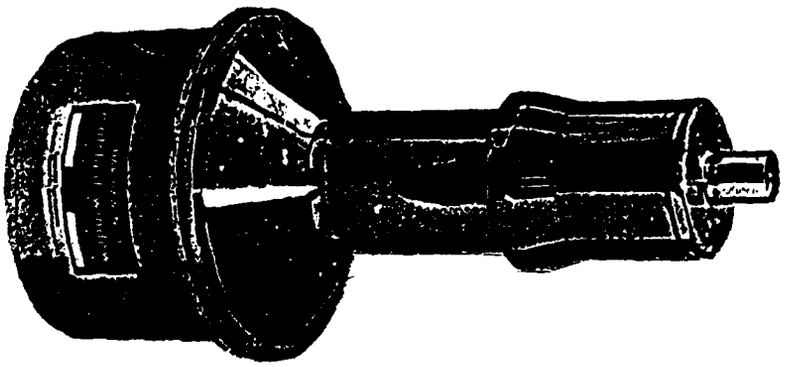
The detection of uranium contamination is fairly straightforward. Among the radiations emitted in the decay of uranium-235 and its daughters is an 80 keV x-ray. Set-up and field calibration of the detector as described in this section allows measurement of the x-ray activity per square meter and thus evaluation of the uranium contamination. Confidence in the accuracy of these measurements is in the ± 25% range.

The detection of plutonium is somewhat more complicated. Plutonium-239 and its daughters emit a 17 keV x-ray which can be detected with a FIDLER-like detector. However, absorption of that relatively low energy x-ray by overburden plus interference by background signals in the same range as the desired x-ray make measurement of the 17 keV a highly uncertain technique. The determination of plutonium contamination can be made more confidently through the following, indirect technique.

Weapons grade plutonium contains several isotopes: in addition to the dominant Pu-239, there is always a trace amount of Pu-241. Pu-241 beta decays, with a half-life of 14.35 years, to Am-241. Am-241 subsequently decays with the emission of a 60-keV x-ray which, like the 80 keV x-ray of uranium, is relatively easy to detect under field conditions. Thus, a most sensitive technique for the detection of weapons grade plutonium is to detect the contaminant Am-241 and infer the accompanying plutonium.

Clearly, this technique requires more information than the direct detection of radiation from the most plentiful isotope, such as knowledge of the age and original assay of the weapon material. However, decay times, weapon age and assay are known or controllable quantities, whereas overburden and its effect on alpha and low energy x-radiation are not. Thus, the community has standardized upon the detection of plutonium via its americium daughter.

A detailed mathematical discussion on the inference of plutonium contamination via the FIDLER can be found in Appendix A. Although relatively straightforward, the process is made somewhat



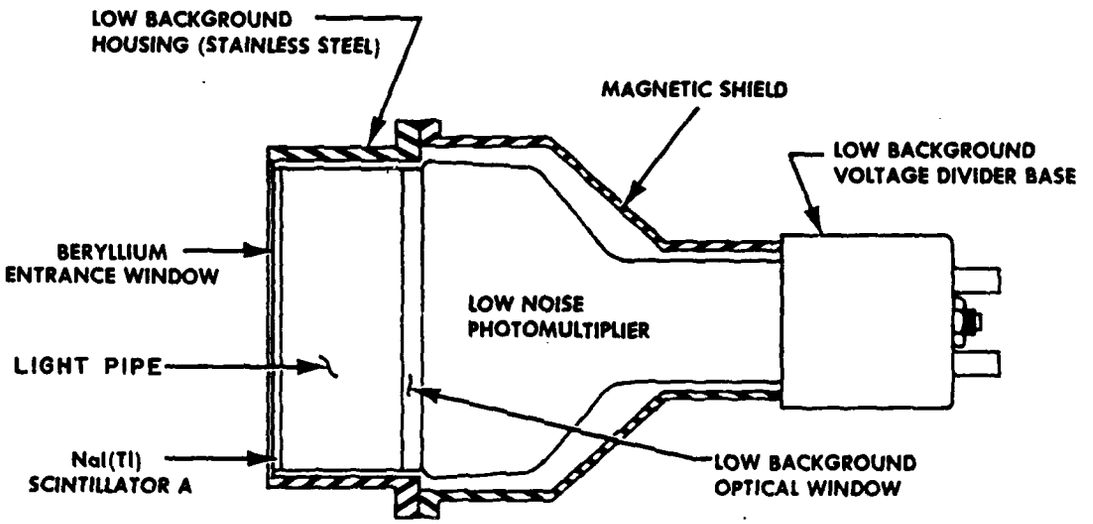


Figure 2. The FIDLER Detector

complex by the number of nuclear, geometric and detector efficiency factors which must be included. In order to facilitate the calculations and calibration needed to measure plutonium contamination by x-ray detection in the field, the Lawrence Livermore National Laboratory has produced a series of utility codes called the HOT SPOT Codes.[1] Available for IBM-compatible computers, as well as the HP-41 calculator systems, the HOT SPOT Codes include an interactive, user-friendly utility routine called FIDLER which steps a user through the process of calibrating an x-ray detector and converting the subsequent measurements to an evaluation of plutonium deposition. Although named for a particular detector, the FIDLER code is applicable to any x-ray detector if the full calibration technique, involving a known americium calibration source, is used.

The field calibration technique implemented through the FIDLER code and used with the FIDLER detector is mathematically developed in Appendix A.

VII. LABORATORY TECHNIQUES

As discussed above, laboratory procedures are necessary to make quantitative measurements of radiation contamination. For this reason, each of the service response forces has a mobile laboratory for deployment to an accident site. Although specific instrumentation will vary, the types of laboratory analyses fall into three categories: gamma and x-ray spectroscopy, alpha-beta counting and liquid scintillation.

1. Gamma and x-ray Spectroscopy

The major tools involved in gamma and x-ray spectroscopy are a reasonably high resolution gamma/x-ray detector (such as a GeLi or selectively high resolution NaI) and a multi-channel analyzer. With this equipment, it is possible to accurately determine the energies of the gamma and x-radiation emitted by a contaminated sample. Generally, spectroscopic techniques are not used for absolute measurements of amount of contamination (e.g. microcuries) in a sample. However, by adjusting for the energy dependence of detection efficiencies and using standard spectral unfolding techniques, it is possible to accurately determine the relative amounts of various isotopes present in the contaminant. Recalling the discussions in the preceding sections, one can see immediate application for such information: For example, spectroscopy allows determination of the relative abundance of Am-241

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1. Steven G. Homann, *HOT SPOT Health Physics Codes*, Lawrence Livermore Laboratory Report M-161 (April 1985)

to Pu-239, resulting in accurate calibration of the most sensitive (FIDLER) survey techniques.

2. Alpha-Beta Counting

Another laboratory technique, alpha-beta counting, does result in a reasonably accurate determination of the absolute amount of contamination in a sample. Two types of counters are common and both are fairly simple in principle. In one, a reasonably sensitive alpha-beta detector, such as a thin layer of ZnS mated to a photomultiplier tube, is mounted in a chamber that is shielded to remove background radiation. A sample, made very thin to minimize self-absorption, is inserted into the chamber under the detector. In some apparatus, air is evacuated from the chamber to eliminate air absorption of the radiation. The count rate is then measured. Knowing the geometry of the experiment permits translating the count rate to an absolute evaluation of sample activity.

Another alpha-beta technique invclves equipment such as gas-flow proportional counters. In these devices, a sample is inserted into the chamber of a proportional counter. The counter is then activated: Any emitted radiation causes ionization of the gas in the counter which is electronically amplified and counted.

In both types of alpha-beta counter, the most difficult, sensitive part of the experiment is the sample preparation. In order to achieve absolute measurements of activity, it is essential to minimize absorption of the radiation by the overburden caused by the sample itself. Techniques used include dissolution of the sample onto a sample holder: evaporation of the solvent leaves a very thin, negligibly absorbing sample. Clearly, quantitative alpha-beta counting is a difficult, time-consuming process.

3. Liquid Scintillation

In a few cases, notably in the detection of beta radiation from tritium, the energy of the radiation is so low - and the resultant absorption is so high - that solid samples cannot be used for quantitative analysis. In these cases, it may be possible to dissolve the contaminant in a scintillating liquid. Glass vials of such liquid can then be placed in a dark chamber and the resulting scintillation light pulses counted using photomultipliers.

Again, the outstanding difficulty with this process is in the sample preparation. Scintillation liquids are extremely sensitive to most impurities which tend to quench the output of light pulses. As a result, the most common technique for liquid scintillation sample gathering is to wipe a fixed area (typically 100 square centimeters) of a hard surface in the contaminated

area with a small piece of cloth. The cloth can then be totally immersed in scintillation liquid in such a way that subsequent light emission will be visible to one of the photomultipliers in the analysis chamber. Alternatively, the cloth can be replaced by a special plastic material that dissolves in scintillation liquid without significantly quenching light output. In either case, the technique works best when the contamination can be gathered without large amounts of local dirt, oil, etc.

VIII. SUMMARY

In summary, quantitative measurements of radioactive contamination in the field is extremely difficult. Particles having short ranges, such as alpha and low energy beta radiation, are significantly and incalculably affected by minute amounts of dust or precipitation. Therefore, detection - rather than measurement - is a more realistic goal for alpha-beta surveys. More penetrating radiations, such as gamma and higher energy x-rays, are less affected by such overburden; however, these require special attention to field calibration techniques in order to convert meter readings to contamination estimates.

Field survey of uranium is best accomplished through measurement of x-rays in the 60-80 keV range emitted by uranium isotopes and daughters. For plutonium, the best technique is to detect the accompanying contaminant Am-241, which emits a strong 60 keV x-ray. Knowing the original assay and the age of the weapon, the ratio of plutonium to americium can be accurately calculated and thus the total plutonium contamination determined.

Many of the overwhelming factors which can not be controlled in a field environment can be managed in a laboratory: thus, all of the response services have mobile laboratory facilities which can be brought to an accident/incident site. Typically, the capabilities that can be brought to bear include gamma spectroscopy, low background counting for very thin alpha- and beta-emitting samples and liquid scintillation counters for extremely low energy beta emitters such as tritium.

APPENDIX A

The Inference of Pu Contamination Density via the FIDLER

PURPOSE

The purpose of this little treatise is to explain the inference of plutonium contamination, as might be expected in case of an accident involving the burning of a plutonium-containing munition, from the low-energy gamma (x-ray) measurements that can be made with the FIDLER probe.

BACKGROUND

The need to use indirect measurement techniques for the quantitative measurement of plutonium is manifest to anyone who has tried to directly detect the emanations from plutonium itself. Basically, Pu-239, the most common isotope of plutonium (Pu), is an alpha emitter with radiations in the range of 5 MeV. Unfortunately, the energy loss per length of path of a 5 MeV or lower alpha particle passing through any material is very high. (A 5 MeV alpha has a range of about 3.5 cm in air and 0.0025 cm in aluminum, whereas an equally energetic gamma has a half length greater than 9 cm in aluminum.) As a result, alpha detectors must have extremely thin windows to allow the particles to enter the detection region: This results in alpha detectors being extremely fragile, and notoriously impractical for field exercises.

More seriously, the extremely short range of alpha particles through any material makes alpha measurement prohibitively sensitive to shielding matter. Thus, a minute amount of dust over a contaminated area will dramatically alter an alpha radiation field and consequently the perceived level of contamination.

As a result, the radiation survey community has developed indirect means of inferring the level of Pu contamination. Basically, these methods involve measuring radiations from other isotopes which are present with Pu-239. A knowledge of the contamination level of these isotopes can then be scaled to determine the Pu level. Specifically, the Broken Arrow Response Kit (BARK) contains a Field Instrument for the Detection of Low Energy Radiation (FIDLER) detector probe which was designed to be particularly efficient in the detection of low energy gamma radiation (x-rays). Using this probe, it is practical to make quantitative measurements of the amount of 17 keV and 60 keV gamma rays produced by Am-241, a companion to weapon grade plutonium.

This treatise provides the technique and factors needed to relate a given COUNT RATE produced by the detection of 17 or 60 keV gamma rays to the associated plutonium contamination.

Specific Activity of Pu and Am-241

Plutonium contamination is a mixture of Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, and Am-241, where the Am-241 is a daughter of the beta decay of Pu-241.

$$^{241}Pu \longrightarrow \beta^- + {}^{241}\dot{A}m$$

For this discussion, we assume that the mixture is isotropic in the contaminated area. We also assume that we can ignore the small mass difference between the various isotopes and use an average atomic mass. Referring to the hypothetical assay shown in Table A-1, we take that average mass to be 239.3.

TABLE A-1. A Typical Assay of Plutonium Isotopes

Isotope	%by mass(1972)	%by mass(1982)	1/2-life(yrs.)
Pu-238	0.	0.	87.74
Pu-239	81.7	81.7	24,300.
Pu-240	5.6	5.6	6,600.
Pu-241	1.6	0.95	13.2
Pu-242	0.	0.	380,000.
Am-241	11.1	11.59	470.

The activity emanating from mass m_j of isotope j can be calculated from:

$$m_j \bullet \frac{\text{No. of atoms}}{\text{mass}} \bullet \frac{\text{Activity}}{\text{atom}}$$

In turn, the number of atoms per mass can be found from $\dot{N}$, Avogadro's number (the number of atoms per gram-mole) and the average mass:

$$\frac{\text{No. of atoms}}{\text{mass}} = \dot{N}/239.3 = 2.52 \times 10^{21} \text{ atoms/gr.}$$

The relationship between the activity per atom and the half-life ($t_{1/2}$) is found from the Law of Radioactive Decay:

$$dN/dt = -\lambda N$$

$$\text{with solution } N = N_0 e^{-\lambda t}$$

$$\frac{\text{Activity}}{\text{atom}} = \frac{-dN/dt}{N} = \lambda = 0.693/t_{\frac{1}{2}}$$

Putting this together, the total activity (disintegrations/time) is given by:

$$\text{Total Activity}\left[\frac{\text{disint}}{\text{yr}}\right] = \sum_j m_j\,[\text{gr}] \cdot \frac{2.52 \times 10^{21}}{[\text{gr}]} \cdot \frac{0.693}{t_{\frac{1}{2}j}\,[\text{yr}]}$$

where m_j is the mass and $t_{1/2\ j}$ is the half-life of isotope j. (Here, we introduce the use of [ ] to indicate the dimensionality/units of the various quantities.) Since we are usually interested in the contamination in terms of areal density ($\mu gr/m^2$), we can rearrange the Total Activity equation as follows. Let the total mass be expressed in terms of the fractional weights of the isotopes in the mixture as:

$$\text{Total Mass}\,[\text{gr}] = \sum_j m_j\,[\text{gr}] = M \cdot \sum_j f_j$$

The Total Activity per Area can be expressed as:

$$\frac{\text{Total Activity}}{\text{Area}}\left[\frac{\frac{\text{disint}}{\text{yr}}}{\text{m}^2}\right] = \frac{M[\text{gr}]}{\text{Area}[\text{m}^2]} \times \sum_j f_j \cdot 2.52 \times 10^{21} \cdot \frac{0.693}{t_{\frac{1}{2}j}\,[\text{yr}]}$$

Finally, converting to micrograms and minutes and using C for the contamination density, we have:

$$\frac{\text{Total Activity}}{\text{Area}}\left[\frac{\text{disint}}{\text{min}}\right] = C\left[\frac{\mu gr}{\text{m}^2}\right] \cdot \sum_j 3.32 \times 10^9 \cdot \frac{f_j}{t_{\frac{1}{2}j}[\text{yr}]}$$

Relating the Contamination per Area to FIDLER Reading

The final, important chapter of this treatise is to relate the FIDLER readings - which are in counts per minute caused by 60 (or 17) keV gammas to density of Pu per area of ground. To do this, it is essential to know the number of 60 keV (or 17 keV) gammas per disintegration for the various isotopes. This factor is listed in Table 2.

TABLE A-2. Selected Radioactivity Data on Pu - Am Isotopes

Isotope	Half-life (yrs)	Spec. Activity (dis/min/μgr)	17keV per dis.	60keV per dis.
Pu-238	8.77e1	3.78e7	0.106	
Pu-239	2.41e4	1.38e5	0.048	
Pu-240	6.57e3	5.05e5	0.1	
Pu-241	1.44e1	2.31e8	0.0	
Pu-242	3.76e5	8.83e3	0.1	
Am-241	4.33e2	7.67e6	0.376	0.36

Now, the reading on a FIDLER depends upon 1) the activity density (contamination per area), 2) the number of gammas per disintegration, 3) the geometry of the probe relative to the ground, and 4) the efficiency of the probe in detecting gammas which hit the active detector area. Symbolically, that can be written:

$$\text{Count Rate} = \frac{\text{Total Activity}}{\text{Area}} \bullet \text{Branching Ratio} \bullet \text{Geometrical Factor} \bullet \text{Probe Efficiency}$$

$$\left[\frac{cts}{min}\right] = \left[\frac{\frac{disint}{min}}{m^2}\right] \bullet \left[\frac{\gamma_{emit}}{disint}\right] \bullet \left[\frac{\gamma_{hit\ probe}}{\gamma_{emit/m^2}}\right] \bullet \left[\frac{cts}{\gamma_{hit\ probe}}\right]$$

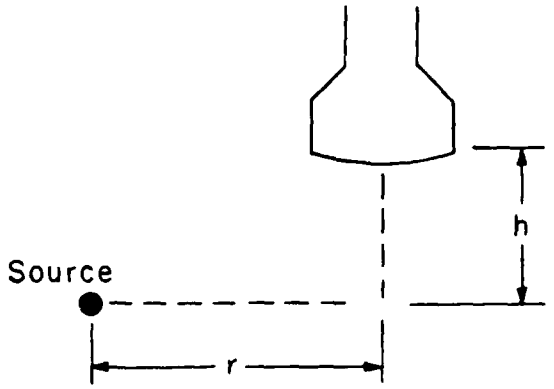
where one must recall that the all references to gammas refer only to those in the energy range of interest (17 keV or 60 keV). The first two terms, Activity Density and Branching Ratio (gammas/disintegration) were discussed above. It remains to discuss the final two factors, the Geometrical factor and the Detector Efficiency.

It turns out that the standardization technique used by the US Army Radiation Control (RADCON) Team does not determine the Geometrical and Efficiency factors independently. Rather, it is most convenient to use a hybrid technique to accurately and field-expediently solve for the two terms together. To help see the derivation, the dimensional analysis begun above will be carried forth here.

First, in the laboratory, we measure a constant geometrical hybrid constant K(h).

$$K(h) = 2\pi \int_0^\infty \frac{dr \bullet r \bullet X(r,h)}{X(o,h)}$$

X(r,h) is the count rate from a source radially out a distance r from the probe, which is at a height h above the monitored surface, as shown.



K(h) is the relationship between a point source below the probe (which is used for calibration) and a uniformly distributed source over the ground. The dimensionality of K(h) is:

$$K(h) = \left[\frac{\gamma_{hit} \cdot \epsilon_{ff} \cdot m^2}{\gamma_{0hit} \cdot \epsilon_{ff}} \right]$$

where $\gamma_{0\ hit}$ refers to γ_{hit} emitted at r = 0.

Note that the above relationship tacitly assumes that the efficiency (ϵ_{ff}) is approximately constant for all radiations of interest which can actually hit the active area of the detector.

K(h) can be evaluated by moving a source out radially out from under the FIDLER probe, taking measurements at selected points, and performing the indicated mathematics. If we symbolically divide top and bottom of the above expression by γ_{emit} and rearrange we get:

$$K(h) = \left[\frac{\gamma_{hit}}{\gamma_{emit}/m^2} \right] \Big/ \left[\frac{\gamma_{0\,hit}}{\gamma_{emit}} \right]$$

Independently, immediately before going out into the field, a known source, Q_{calib}, is placed below the probe and the resulting count rate, X_{calib}, is recorded. Dimensionally, we can write:

$$\frac{X_{calib.}}{Q_{calib.}} = \left[\frac{cts/min}{\gamma_{emit/min}}\right]$$

Of course, it is assumed that all meter readings have been background-corrected. Now, we multiply K(h) by the X/Q ratio to get:

$$K(h) \cdot \frac{X_{calib}}{Q_{calib}} = \frac{\left[\frac{\gamma_{hit}}{\gamma_{emit/m^2}}\right]}{\left[\frac{\gamma_{0\,hit}}{\gamma_{emit}}\right]} \times \left[\frac{cts/min}{\gamma_{emit/min}}\right] = \left[\frac{\gamma_{hit}}{\gamma_{emit/m^2}}\right] \times \left[\frac{cts}{\gamma_{hit}}\right]$$

Comparing to the count rate equation, we see that the K(h), X/Q product does equal the last two terms in the expression.

The ULTIMATE Relationship

All of the above can now be put into the count rate equation:

$$\text{Count Rate}\left[\frac{cts}{min}\right] = \left[C\left[\frac{\mu gr}{m^2}\right] \times \sum_j f_j \cdot \frac{3.32 \times 10^9}{t_{\frac{1}{2}j}\,[yr]}\right] \times \left[\text{Branching Ratio}\right]_j \times K(h) \times \frac{X_{calib}}{Q_{calib}}$$

If we now solve for **C**, the contamination density, we have the desired, ULTIMATELY useful relationship between Pu contamination and FIDLER count rate from measurable gammas:

$$C\left[\frac{\mu gr}{m^2}\right] = \frac{\text{Count Rate}\ [cts/min]}{\sum_j f_j \times \frac{3.32 \times 10^9}{t_{\frac{1}{2}j}\,[yr]} \times \text{Branching Ratio}\,j \times K(h) \times \frac{X_{calib}}{Q_{calib}}}$$

$$= F \times \text{Count Rate}\ [cts/min]$$

where the calibration factor, **F**, is the inverse of the above denominator. The geometric factor, K(h), can be measured for any detector. The branching ratio and half-lives are also known. Therefore, it is only necessary to determine the assay at some point in time, which allows computing the f_js, and to make the field measurement X of the known source, Q.

In order to facilitate the calculations and calibration needed to measure plutonium contamination by x-ray detection in the field, the Lawrence Livermore National Laboratory has produced a series of utility codes called the HOT SPOT Codes.[A-1] Available for IBM-compatible computers, as well as the HP-41 calculator systems, the HOT SPOT Codes include an interactive, user-friendly utility routine called FIDLER which steps a user through the process of calibrating an x-ray detector and converting the subsequent measurements to an evaluation of plutonium deposition.

Particularly useful in the FIDLER code is the provision to aid in the measurement of the geometric K(h) factor for any specific detector. Measurements made at the Ballistic Research Laboratory and the Lawrence Livermore National Laboratory[A-2] have shown that the value of K(h) for h = 30cm can vary from less than 0.4 m^2 to over 1.0 m^2, apparently depending upon external configuration and subtle internal details of a particular FIDLER probe. For this reason, the FIDLER code contains both a detailed laboratory procedure and a field-expedient procedure for determining K(h) for a given detector. The code also provides a default value of 0.5 m^2. This value was chosen to give a relatively conservative indication of contamination per count rate.

Although named for a particular detector, the FIDLER code is applicable to any x-ray detector if the full calibration technique, involving a known americium calibration source, is used.

A-1. Steven G. Homann, *HOT SPOT Health Physics Codes*, Lawrence Livermore Laboratory Report M-161 (April 1985)

A-2. Steven G. Homann, Emergency Preparedness & Response Program, Lawrence Livermore National Laboratory, private communication.

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